

STATISTICAL ANALYSIS OF IN-SERVICE EVOLUTION OF  
AN AIRPORT ASPHALT SURFACING

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## ABSTRACT

Significant testing was performed on cores recovered from the trafficked and un-trafficked portions of a typical Australian airport runway surface approximately two years after paving. The relative density, aggregate orientation, resilient modulus, wheel tracking and interface shear resistance were measured and statistically compared. Interface shear resistance included strength, modulus and work/energy measurements. With the exception of the interface's shear modulus, traffic was found to have a statistically significant impact on all parameters compared.

Aircraft traffic triggered a substantial change in the asphalt's structure. This evolution of the asphalt structure resulted in a measurable improvement in the surface layer's resilient modulus and interface shear strength. Being typical of airport asphalt used throughout Australia, the measured effects of traffic are expected to be representative of all Australian airport asphalts. Further investigation is needed to determine the rate of evolution of asphalt structure as a function of traffic frequency.

## INTRODUCTION

As part of a broader forensic investigation of an Australian airport's asphalt overlay, significant testing was performed on cores recovered from the trafficked and un-trafficked portions of the runway surface. All cores included the underlying asphalt layer, allowing assessment of the interface. The surface layer was generally 50-60 mm thick and comprised nominal 14 mm sized dense graded Marshall asphalt. The mix design was typical of mixes used for airport surfacing and overlay in Australia as described by Emery [1]. Table 1 presents the key characteristics and mix design parameters against the specification limits. The resurfacing work was performed over a ten month period. Construction included the texturing of the existing surface followed by cleaning and tack coating with a bitumen emulsion. At the time of forensic coring and testing, the surface was approximately two years old.

Table 1.  
Comparison of Key Asphalt Characteristics.

| Parameter                                  | Mix Design Value | Specification Limit |
|--|------------------|---------------------|
| Binder Content (%)                         | 5.8              | Minimum 5.6         |
| Hydrated Lime Content (%)                  | 1                | 0.5 – 1.5           |
| Passing 75 $\mu$ m sieve (%)               | 6.5              | Target 5, Maximum 7 |
| Marshall Stability (kN)                    | 17.5             | Minimum 12          |
| Marshall Flow (mm)                         | 3.1              | Maximum 3.5         |
| Air Voids (%)                              | 4.2              | 3 – 5               |
| Voids in Mineral Aggregate (%)             | 18%              | Minimum 14          |
| Voids filled with binder                   | 76%              | Minimum 75          |
| Tensile Strength Ratio (%)                 | 98               | Minimum 90          |
| Resilient Modulus (MPa)                    | 2,790            | Report only         |
| Indirect Diametrical Tensile Strength (kN) | 960              | Report only         |
| Wheel Tracking (mm)                        | 3.4              | Report only         |

A significant difference was noticed in forensic test results from areas of the pavement that were frequently trafficked by aircraft and those that were not. This prompted a specific statistical assessment of the change in the asphalt's structure and response under aircraft traffic.

The aim of this research was to measure the evolution of various properties and responses of an asphalt surface resulting from frequent heavy aircraft traffic. After background information is presented and the research methods are described, the results from each of the test methods are compared using statistical analysis techniques. Conclusions are then made and the implications for future work described.

## BACKGROUND

Asphalt is a material of very complex mechanical behaviour. Asphalt's internal composition is the agglomeration of binder, active filler, fine and coarse aggregate. The mastic exhibits plastic, elastic and viscous properties which are inherently temperature dependent [2]. While the mastic dominates many mix properties, both the mastic and the aggregate skeleton are important to asphalt performance [3]. In fact, by mass, aggregate comprises some 95% of asphalt's structure and can therefore have a significant impact on the mechanical properties of a surface layer [4].

### Characterisation of Aggregate Skeleton

The aggregate skeleton within asphalt can be measured directly through microstructure assessment or via bulk material characteristics using macrostructure assessment [4]. For microstructure assessment two main approaches have been adopted by other researchers:

- **X-ray Computer Tomography (XCT).** XCT provides an accurate 3D assessment of an aggregate structure. XCT is able to differentiate a broad range of engineering materials with an accuracy of up to 5  $\mu\text{m}$  [5]. Due to its non-destructive nature, XCT can be used to assess the same sample before, during and after wheel tracking or other performance test. It also offers the advantage of being able to measure air void distribution [6].
- **Digital image analysis.** Digital image analysis is well established within the study of geomechanical materials such as clays [7]. Digital image processing includes three major steps; image acquisition, image processing and image analysis [5]. Common software can rapidly calculate the number of contact points, aggregate orientation distribution and aggregate segregation measures [8]. Requiring only a digital camera and software, digital image analysis offers an economical and rapid assessment of the aggregate skeleton on a 2D basis.

Significant research has been conducted on the structure of asphalt skeletons using both methods. Image analysis was used by Hamzah et al. [9] to compare the aggregate skeletons produced by different compaction methods. Lv et al. [10] analysed the voids, aggregate orientation and segregation of numerous asphalt mixes using similar techniques. In contrast, Masad et al. [6] used XCT to assess the air voids distribution and segregation of various asphalt mixtures prepared with various compaction methods. The effect of different compaction methods on asphalt structure was also investigated by Kutay et al. [11] using XCT. Tashman et al. [12] also used XCT to assess the aggregate structure but only as a means of verifying a viscoplastic model for asphalt deformation.

## Structural Factors Affecting Performance

Research has shown asphalt performance to be affected by variation in the orientation and spatial distribution of coarse aggregate particles [8]. The number and length of contact points is known to influence asphalt's shear strength [13] as does the distribution of the air voids within the sample [14]. Coarse and fine aggregate angularity provides an indication of aggregate internal friction properties and deformation resistance [15]. For asphalt samples of identical mix design and construction process, changes in the orientation of the particles within the aggregate skeleton can explain significant differences in performance [4].

## Aggregate Orientation

Aggregate orientation cannot be expressed as a single value or described by a single parameter [16]. Many researchers have used a combination of average angle of inclination ( $\hat{\theta}$ ) and vector magnitude ( $\Delta$ ) [4, 5, 9, 10, 14, 17, 18]. These concepts were advanced to their current form by Curray [19] and are defined in Equations 1 and 2.

$$\Delta(\%) = \frac{100}{n} \sqrt{(\sum \sin 2\theta_k)^2 + (\sum \cos 2\theta_k)^2} \dots\dots\dots \text{Equation 1}$$

$$\hat{\theta}(\circ) = \frac{\sum |\theta_k|}{n} \dots\dots\dots \text{Equation 2}$$

Where n = the number of aggregate particles in the image, each with a major axis angle of inclination of  $\theta_k$ .  $\Delta$  varies from 0% to 100% where 0 represents a completely random distribution of aggregate particle orientation and 100 represents all particles being in the same alignment.  $\hat{\theta}$  varies from 0° to 90° while  $\theta_k$  ranges from -90° to 90° [14].

With the ready availability of digital cameras and computational software to analyse the images, much effort has recently been made assessing the orientation of aggregate particles resulting from different compaction methods. These efforts peaked in response to the introduction of the Superpave gyratory compactor in the USA [8]. Studies have assessed aggregate orientation with respect to the horizontal and vertical axis, as well as radially (for circularly compacted samples prepared in the lab).

Compaction processes have been shown to significantly change the aggregate orientation and structure [9]. For example Lv et al. [10] reported average angles of inclination of 33 to 36 for gyratory compacted samples and 35 to 47 for vibratory compacted samples of various grading envelopes. In the same study, vector magnitudes of 25 to 30 for gyratory compacted samples and 15 to 25 for vibratory compaction were reported. Vector magnitudes of 48 to 52 were reported by Bessa et al. [17] for slab compacted samples. Masad et al. [13] reported vector magnitudes of around 25 and 37 and angles of inclination of around 32 and 37 for gyratory and kneading compactors respectively.

Tashman et al. [5] stated that the vector magnitude after compaction typically ranges from 30 to 50 for vertical sections, while it does not generally exceed 0.1 for horizontal sections. The rate of change in aggregate structure during compaction has also been studied. With increasing gyrations of a gyratory compactor the average aggregate orientation angle reduced from 41 to 33 over 100 cycles and then increased again to around 38. At the same time the vector magnitude increased from 15 to 44 and then dropped to 22 [6].

## **Effect of Traffic**

While a large number of studies have investigated the aggregate skeleton of asphalt, comparatively little work has been done to assess the change in orientation or asphalt response under the action of post-construction traffic. Collop et al. [20] found that a year of trafficking increased the internal shear strength of asphalt by an average of 30%. Mohammad et al. [21] reported that increased asphalt density resulted in increased interface shear strength, but whether the increase in density was due to compactive effort or trafficking was not detailed. Similarly, Oeser et al. [22] showed that densification of asphalt lead to increased inter-particle contact and a resultant ‘hardening’ of the mix.

Kondo et al. [23] investigated the movement and reorientation of aggregate particles during Cooper’s wheel tracking test. Aggregates were found to move in vertical, horizontal and rotational directions, giving a zero average net movement. Holleran et al. [15] similarly reported significant reorientation of aggregate particles during wheel tracking in stone mastic asphalt mixes containing elongated particles, which tended to a more horizontal alignment under repeated loading.

Chen et al. [4] reported aggregate reorientation during the wheel tracking test in three phases (primary, secondary and tertiary). This closely reflected rut depth growth and is similar to the widely recognised three phases of asphalt flow [24]. During the primary phase, the aggregate rotated to a stable orientation. In the secondary phase, the particles remained stable. In the tertiary phase, significant reorientation and movement occurred as the asphalt deformed and rutted substantially.

## **INVESTIGATION METHODS**

The methods utilised in this investigation were focused on the statistical comparison of key parameters of nominally identical samples except for their exposure to frequent aircraft traffic. As outlined previously the asphalt mix was compliant with the typical Australian specification for airport asphalt.

### **Basis of Comparisons**

Asphalt samples can be compared in a number of ways. The methods generally either measure the properties of the various constituents within the mix, the relative proportions and distribution of those constituents, the macro properties of the asphalt or the response of the asphalt to applied load. Because comparisons were being made between trafficked and un-trafficked samples from the same asphalt material, assessment of the constituents and their proportion/distribution within the samples was not performed.

Of the data available, the following were considered likely to be influenced by trafficking and were therefore utilised as the basis for comparing the trafficked and un-trafficked samples:

- **Relative Density.** Trafficking may have increased the asphalt's density in comparison to un-trafficked asphalt, which would remain similar to its constructed density.
- **Aggregate Orientation.** Trafficking may have altered the structural skeleton through reorientation of the aggregate particles to a more horizontal alignment.
- **Resilient Modulus.** An increase in density or reorientation of the aggregate particles would likely result in an increase in the modulus.
- **Wheel Tracking.** An increase in the density would effectively 'consume' an amount of the densification potential under wheel tracking. Any structural improvement due to reorientation of the aggregate to a more stable skeleton would also reduce future rut potential.
- **Interface Shear Resistance.** Increased embedment of the surface layer aggregate into the underlying surface may increase the interface shear resistance through improved aggregate embedment.

## Test Methods

Existing Australian Standard (AS) test methods were utilised where available. Where no AS test was available, other established test methods were adopted. In the case of the interface shear resistance a protocol was developed based on the direct shear-box test method, similar to that described by Canestrari et al. [25] as the ASTRA test.

### Relative Density

The relative density of each sample was measured from cores recovered from the surface. The 100 mm diameter cores were trimmed just above the interface and the density measured and compared to the laboratory prepared Marshall density for that Lot of asphalt from the project quality assurance records. All samples were prepared according to AS 2891.1 and tested in accordance with the Australian Airports Association Method of Test 002.

### Aggregate Orientation

Aggregate orientation was evaluated by 2D digital image analysis using the software i-Pas 2, developed at the University of Wisconsin-Madison and described by Sefidmazgi et al. [26]. The software examines a digital image of a cross section of the asphalt sample and requires a number of key mix parameters such as voids in the mineral aggregate, binder content and grading. The software then analyses the image and calculates the contact lengths, geometry, location and angle to the horizontal of each aggregate particle. From this data, the vector magnitude and average angle of inclination were calculated.

### Resilient Modulus

The resilient modulus was measured from cores recovered from the surface. The 100 mm diameter cores were trimmed just above the interface and then tested by the indirect tension method in accordance with AS 2891.13.1. Standard test conditions were utilised and a test

temperature of 25°C was adopted as is common practice in Australia for modulus testing of airport asphalt.

### Wheel Tracking

The 200 mm diameter cores recovered from the surface were tested under the Australian protocol for the Cooper's wheel tracker. The samples were trimmed just above the interface and held in a jig that allowed the wheel tracker to traverse across the sample surface as detailed in Austroads AG:PT/T220. The Australian test is performed at a load of 700 N over 10,000 cycles. Samples were conditioned to 60°C as detailed in Austroads AG:PT/T231.

### Interface Shear Resistance

Interface shear resistance was measured by a direct shear test of the interface from cores obtained from the surface. Interface Shear Strength (ISS), Interface Shear Modulus (ISM) and Interface Shear Work (ISW) were calculated. ISS was calculated as the peak shear load divided by the initial cross sectional area of the interface. ISM was calculated as the gradient of the elastic portion of the plot of shear stress as a function of shear strain. ISW was calculated as the area under the shear force versus shear deformation plot during the first 10 mm of deformation.

Up to eight cubic samples were cut from each 200 mm core and tested at various normal stresses, ranging from approximately 20 kPa to 700 kPa. This allowed Mohr-Coulomb type envelopes to be generated for each core. Square sectioned samples are not commonly used for direct shear strength testing but were selected to avoid any point-loading associated with imperfectly matching circular sections.

Direct shear testing was performed on samples conditioned to 55°C to represent the mean summer pavement temperature in most parts of Australia. The samples were sheared at a constant 50 mm per minute rate of deformation.

### **Statistical Analysis**

The various tests results were compared using a range of statistical techniques. For direct comparison of results where the only explanatory variable was the dichotomous factor ('trafficked' or 'un-trafficked') a Student's T-test was utilised. As the data was not paired, sample sizes for each group could be different and the variances were not known to be equal, a single-sided Welch's version of the T-test was performed [27].

For direct shear resistance testing both the dichotomous ('trafficked' or 'un-trafficked') and the applied normal stress were considered as explanatory variables. It is well established that interface shear resistance increases linearly with increasing normal stress [28]. Rather than separately compare the results for tests performed at different levels of normal stress, a linear regression analysis was performed. Each of the measures of interface shear resistance was modelled as a linear function of the normal stress and whether or not they were trafficked. The statistical significance of the trafficking was obtained from the p-value associated with its coefficient from the regression analysis [29]. Prior to final regression analysis, any outliers were identified using Cook's distance and by inspection of the plots of residuals and removed from the data set. The normality and variance of the residuals were also checked at that time.

## RESULTS AND ANALYSIS

The analysis of the results was performed ‘parameter-by-parameter’ using the statistical techniques described above. The consistence of the effect of aircraft traffic across each of the various parameters was then considered.

### Relative Density

A summary of the relative density data is presented in Table 2. With a T-test p-value of 0.05 and by comparison of the mean values, it was determined that the trafficked areas of the surface had a statistically significantly higher relative density than the un-trafficked areas. On average trafficked areas had a 1.5% higher relative density. A moderate increase in density of a viscoplastic material under repeated heavy loading was intuitively expected.

Table 2.  
Relative Density Summary.

| Statistic          | Trafficked                          | Un-trafficked |
|--------------------|-------------------------------------|---------------|
| Mean               | 99.5%                               | 98.0%         |
| Standard Deviation | 1.3%                                | 1.3%          |
| p-value            | 0.05 for 30 degrees of freedom (df) |               |

### Aggregate Orientation

Table 3 summarises the vector magnitude and average angle of inclination results from both trafficked and un-trafficked areas of the surface. With a T-test p-value of less than 0.01 and by comparison of the mean values, it was determined that the trafficked areas of the surface had a statistically significantly lower average angle of inclination than the un-trafficked areas of the same asphalt. Similarly, with a p-value of 0.02, the trafficked samples showed statistically significantly higher vector magnitudes than un-trafficked samples. This suggested that frequent aircraft traffic had caused the aggregate particles to become more horizontally aligned. It is also noted that the vector magnitude values for both trafficked and un-trafficked samples are at the upper end of those reported in literature. This may reflect the high quality of the asphalt mix and the high level of compaction required during construction of an airport surface layer. Most vector magnitudes reported in the literature were measured on asphalt mixes compacted in the laboratory and manufactured to road specifications.

Table 3.  
Aggregate Orientation Summary for Matthews Dust.

| Statistic          | Average Angle of Inclination ( $\hat{\theta}$ ) |               | Vector Magnitude ( $\Delta$ ) |               |
|--------------------|---|---------------|-------------------------------|---------------|
|                    | Trafficked                                      | Un-trafficked | Trafficked                    | Un-trafficked |
| Mean               | 32.8°   | 39.8°         | 69.1%                         | 59.0%         |
| Standard Deviation | 0.93°   | 2.73°         | 4.6%                          | 6.4%          |
| p-value            | < 0.01 for 7 df                                 |               | 0.02 for 7 df                 |               |



## Resilient Modulus

Resilient modulus data from both trafficked and un-trafficked areas of the asphalt surface layer are summarised in Table 4. With a T-test p-value of 0.04 and by comparison of the mean values, the trafficked areas had a statistically significantly higher resilient modulus than the un-trafficked areas. It was anticipated that trafficking would increase the resilient modulus of the asphalt as a result of the increase in density, reduction in air voids and increased aggregate contact and interlock.

Table 4.  
Resilient Modulus Summary.

| Statistic          | Trafficked     | Un-trafficked |
|--------------------|----------------|---------------|
| Mean               | 3,675 MPa      | 3,158 MPa     |
| Standard Deviation | 668 MPa        | 371 MPa       |
| p-value            | 0.04 for 30 df |               |

## Wheel Tracking

Table 5 presents the wheel tracking data from both trafficked and un-trafficked areas of the surface. A T-test p-value of 0.06 and comparison of the mean values indicated that the trafficked areas of the asphalt surface had statistically significantly less rutting potential under wheel tracking than the un-trafficked areas. The wheel tracking test is designed to measure the remaining potential for rutting within an asphalt sample. For a trafficked sample it was not surprising that the remaining rut potential had decreased. It was also expected that the un-trafficked wheel tracking results would be similar to those measured on laboratory prepared samples, assuming that the laboratory compactive effort closely replicated that achieved in the field. The laboratory prepared wheel tracking result was 3.4 mm, which is similar to the un-trafficked average of 3.3 mm.

Table 5.  
Wheel Tracking Summary.

| Statistic          | Trafficked                         | Un-trafficked |
|--------------------|------------------------------------|---------------|
| Mean               | 1.9 mm                             | 3.3 mm        |
| Standard Deviation | 0.6 mm                             | 0.2 mm        |
| p-value            | 0.06 for 6 degrees of freedom (df) |               |

## Interface Shear Resistance

Linear regression models were generated for the interface strength (ISS), modulus (ISM) and work (ISW) separately. The dichotomous variable (trafficked or un-trafficked) was modelled as the dummy variable *Trafficked* with an assigned value of 1 (for trafficked samples) or 0 (for un-trafficked samples).

The ISS, ISM and ISW regression models are shown in Equations 3 to 5. In all cases *Normal* is the normal stress applied during the test and *Trafficked* is the dummy variable described above.

$$ISS = 285 + 0.729 \times Normal + 143 \times Trafficked \dots\dots\dots \text{Equation 3}$$

$$ISM = 119 + 0.061 \times Normal + 4.7 \times Trafficked \dots\dots\dots \text{Equation 4}$$

$$ISW = 3.30 + 0.018 \times Normal + 3.25 \times Trafficked \dots\dots\dots \text{Equation 5}$$

Table 6 presents the regression coefficients for each of the linear models in Equations 3 to 5 and the p-values associated with the statistical significance of the variables *Normal* and *Trafficked*.

Table 6.  
Interface Shear Resistance Summary.

| Predictor | Correlation Coefficient<br>(R <sup>2</sup> ) for Regression | p-value for Factor |            |
|-----------|---|--------------------|------------|
|           |   | Normal             | Trafficked |
| ISS       | 77%   | < 0.01             | 0.01       |
| ISM       | 23%   | 0.01               | 0.70       |
| ISW       | 91%   | < 0.01             | < 0.01     |

From the p-values and the regression models it was concluded that:

- Normal stress is statistically significant in all cases. Based on the work of Uzan et al. [28] and many others that have investigated the shear resistance of interfaces between asphalt layers, this was fully expected.
- Trafficking was not statistically significant for ISM. No other research could be found that addressed whether this should or should not be expected. Although some researchers [30] have suggested that ISM is dominated by the texture of the interface. Further investigation would be required to determine the specific effect of trafficking on evolution of ISM.
- Trafficking was statistically significant for both ISS and ISW. This is consistent with the findings of others [20, 21, 22] where the action of trafficking was shown to improve the interface's shear resistance.

## CONCLUSIONS

Aircraft traffic significantly changed the structure of the asphalt surface investigated and generally improved the response of the asphalt surface layer. The data indicated that aircraft traffic over two years of service:

- Increased the relative density of the surface layer by approximately 1.5%.
- Re-orientated the aggregate particles towards a more horizontal and ordered alignment.
- Increased the resilient modulus of the asphalt by approximately 500 MPa.

- Decreased the remaining rut potential from approximately 3 mm to less than 2 mm.
- Significantly improved the interface shear resistance, particularly the ISS and ISW.

These findings are consistent with those reported by other researchers. They indicate that under repeated heavy aircraft traffic loading:

- Aggregate particles re-orientated to a more stable arrangement, which increased the combined inter-particle contact area and locked-up the matrix.
- During this aggregate re-orientation process, the relative density of the surface layer increased moderately.
- The combined effect of the densification and aggregate re-orientation improved the asphalt mix as well as improving interlayer embedment and interface bonding.
- This structural evolution resulted in increased resilient modulus and improved interface shear resistance.

Additional investigation is needed to determine the rate of structural evolution and improvement response measured in this investigation as a function of traffic frequency. The asphalt surface investigated in this study was typical of airport asphalt used throughout Australia. These findings are therefore expected to be representative of that expected for all Australian airport asphalts trafficked by significant aircraft.

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